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RESEARCH REPORT
Concepts

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LEARNERS' EXPLANATIONS FOR CHEMICAL PHENOMENA

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ABSTRACT: There is a growing body of research which explores the nature of explanation in science classrooms. The vast majority of this work highlights the teacher's role as explainer of scientific phenomena, while little has explored the quality of learners' own explanations. This paper helps redress this inbalance by undertaking an analysis of students' explanations related to aspects of chemical structure and bonding. In this paper we set out our results - an analytical framework for exploring the explanations produced by students within the context of a chemistry course. The primary source of data used in this research derives from interviews with students in the U.K. studying chemistry at University entrance level. These interviews were undertaken as part of a longitudinal study of the development of students' understanding of the chemical bond concept. The data collected has been interrogated to develop an analytical model of learners' explanations in chemistry. [*Chem. Educ. Res. Pract. Eur*.: 2000, *1*, 329-353]

KEYWORDS: *chemical phenomena; student explanations; explanatory power; tautology; anthropomorphism; levels of explanation*

> *"The purpose of science is to produce viable explanations for phenomena."*
> Driver et al., 1996, p.44.

INTRODUCTION

There is a growing body of research which explores the nature of explanation in science classrooms. The vast majority of this work highlights the teacher's role as explainer of scientific phenomena (for example, Ogborn et al. 1996), or facilitator of a learning community (Ritchie, 1998, p.183), with an emphasis on the need for explanations to be meaningful, illuminative and closely tuned to the needs and competencies of the receiving audience, the explanees. The emphasis on the role of explanations is heightened by recent exhortations that the full science curriculum itself should be organised in terms of a series of 'explanatory stories' for schools (Millar & Osborne, 1998). Little of this work has explored the quality of learners' explanations for phenomena.

In this paper we attempt to redress this balance a little. We consider the relationship between a student's explanation, a student's response to a teacher's question, and a student's conception. We also consider the nature of explanations in science and in chemistry. Examples of chemistry students' comments in interviews are then presented and analysed, in order to illustrate key features and variables of student explanations in chemistry. In particular, three key dimensions of student explanations are identified.

Student explanations

The vast bulk of work on students' responses within school science has been within the traditions of 'alternative frameworks' research and studies on 'conceptual change learning'. Learners' explanations have largely been considered as data collected as evidence of the students' conceptualisations of science topics. As a result, a great deal is now known about learners' ideas in many topics (e.g. Driver, et al., 1994). Other workers have focused instead on learners' explanations as evidence for their epistemologies of science (Driver et al., 1996; Duveen, et al., 1993, Solomon, et al., 1994). Whilst this present study has common ground with both of these traditions, our focus here is very much on the nature of the explanations themselves. Our departure from previous work - for the purposes of this paper at least - lie in the differences we see between the shape and intentions between a learner's alternative conception and his or her explanation for a science-based phenomenon.

What is the difference between a student's response to a question, a students' alternative conception and a student's explanation?

1. *Responding: the social imperative*

It is usual social convention to respond to a question. By 'respond' we mean to acknowledge the question, to indicate through some aspect of behaviour that the person questioned recognises that he or she has been asked a question, and does not wish to be seen to ignore the questioner (which would be seen as an impolite, disrespectful, and maybe even an aggressive act). Of course the response may be no more that a shrug of shoulders, or an utterance along the lines - "well, that's a good question". We might say there is a social imperative to respond, to take one's turn in the language game (Lemke, 1990).

Beyond the social imperative to take one's turn, there is surely an imperative - to answer (rather than just respond), to make sense - i.e. to explain. We might say there is a metaphysical imperative which impels us not just to utter at each other, but to build up meaningful discourse by contributing to the construction of frameworks of understanding (c.f. Bruner, 1987). That such an imperative exists is not controversial - the existence of so much of our culture (including science) is evidence, and there is a clear evolutionary case for the natural selection of such a tendency (Mithen, 1998).

Questions - apart from rhetorical ones - may be considered to invite answers, but not all questions invite explanations. For example the response 'oxygen' to the question 'which element has the symbol O?' is an answer, but not an explanation. The types of questions which invite *explanations* rather than just answers may be *typified* as 'why' questions (although we recognise that the *actual* wording may be different: 'how does that happen?', we could paraphrase such questions in terms of "why?"). From what is said above it is clear that *the response* to a question seeking an explanation may not actually be an explanation. For example 'I don't know' is a *valid response* but not an explanation. Nevertheless, many responses to such questions may be seen as *intended* explanations.

2. *Explaining: the metaphysical imperative*

The extent to which such *attempts* at explanation may prove successful is of course a moot point (and a large part of the rationale for our present concerns in this paper). Before we can answer this question we have to briefly consider the criteria by which such success will be measured, and - in the first place - *who* should judge. Clearly, in terms of the social context, an explanation may be seen to have been *somewhat* successful if the questioner recognises the response as an explanation, and somewhat more successful if this audience considers the response to be an *adequate* explanation. As Driver and coworkers noted, "In one sense, an explanation is simply what is accepted by the person who has given it, and by the person who has received it, as an explanation." (Driver et al., 1996, p.26.)

Much of the research into learners' ideas in science involves probes set up by researchers, who are the audience for any response, and the judges of the quality of any explanations offered. Of course, research also collects more naturalistic data where the questioner is a teacher or peer. Here, then, are three categories of potential audience who may not agree on what passes for an explanation. Driver et al. characterised school pupils at three levels of understanding about explanation.

Pupils using 'phenomenon-based reasoning' did not distinguish between a description and an explanation (p.113). At a higher level of 'relation based reasoning', explanation was seen in terms of correlations which were seen as causal (and following simple linear sequences with no room for multiple causes) (p.113). At the highest level of 'model-based reasoning' pupils were able to use models as theoretical constructs which could provide explanatory 'stories', and were able to accept that more than one model could be useful in any particular context (p.114).

Such model-based reasoning is most like the scientific explanation. According to Trusted "explanations provide descriptions, suggest causal links and place the explicandum in a broader Trusted distinguishes between several types of explanation, and her category of 'empirical explanations' is of particular interest to us here. According to Trusted satisfactory explanations:

- help us to answer the questions prompted by natural curiosity (p.2)
- demonstrate a logical connection between the concepts of knowledge and discovery and the concept of explanation (p.2)
- relate the phenomenon to be explained (the explicandum) to some accepted regularity, that is to an empirical law (p.52)
- are in the form of a logical argument from premises (the law(s) and particulars) to conclusion (pp.52-53.)

> "A full causal explanation, an explanation as to *why* things happen or *why* they are as they are, consists of a statement of an accepted law (or laws) and some other statement(s) relating the particular circumstances to it (or to them) so that from all these the *explicandum* can be deduced.
> (Trusted, 1987, p.52.)

It will be seen that producing a good explanation is hard work, because there are some fairly exacting standards and criteria at play. 'No production' is much less mentally taxing than 'high quality production'. (Therefore the social imperative to produce an explanation is important. Factors such as the time available, what exactly is expected, the initial information provided etc., are likely to strongly influence the nature of any explanation produced.) Maybe we should be judging 'good explanations' against 'good essay' or 'good composition' standards, in that the:

(i) necessary components are present;
(ii) interrelationships between components are explicit and relevant;
(iii) components are logically structured;
(iv) components are related to overriding abstract principles;
(v) overall presentation has regard for audience
(vi) explanation has regard for other related explanations.

Usually, as science educators, we are interested in how well learners can (re)produce the conventional explanations of orthodox science - or perhaps rather how they *construct* explanations that are *consistent with* the theoretical corpus of knowledge that is the current orthodoxy of science. Only a sub-set of students' explanations would be considered as orthodox scientific explanations (see Figure 1). Sometimes such successful productions may primarily be generated on-the-hoof, without reflecting any particularly strongly held beliefs (c.f. Claxton, 1993). More often the learners' existing cognitive structure will be a key determinant of any explanations produced (Figure 1). As research shows that learners hold such a wide variety of alternative ideas (alternative to orthodox science, that is), many responses that *formally* meet the criteria for sound explanations, may well not be good scientific explanations.

Considered views would reflect aspects of the learner's cognitive structure, including such elements as basic metaphysical commitments (Duschl & Hamilton, 1992; Hewson & Hewson, 1984) as well as specific conceptions about aspects of chemistry. Where the conceptions applied reflect orthodox chemistry the explanation produced may be a good scientific explanation - and where the respondent's conceptions are at variance with orthodox chemistry these alternative conceptions may lead to 'alternative explanations'. That is, explanations which are formally correct within an alternative (i.e. 'false') system of knowledge where, say, oxidation must include reaction with oxygen, or where all liquids are considered to contain water.

The nature of scientific explanations

In summary, then, in our view explanations in science:

(i) must be 'satisfactory', must 'do the job'. That is, they must offer a 'story' congruent with contemporary science orthodoxy;
(ii) say how something comes about. Explaining makes sense so that issues involved are no longer arbitrary, so that the unfolding of the explanation then relates to the audience and makes sense in everyday terms. This is when the explanation stops, when it is 'how things are' (Ogborn et al, p.10);

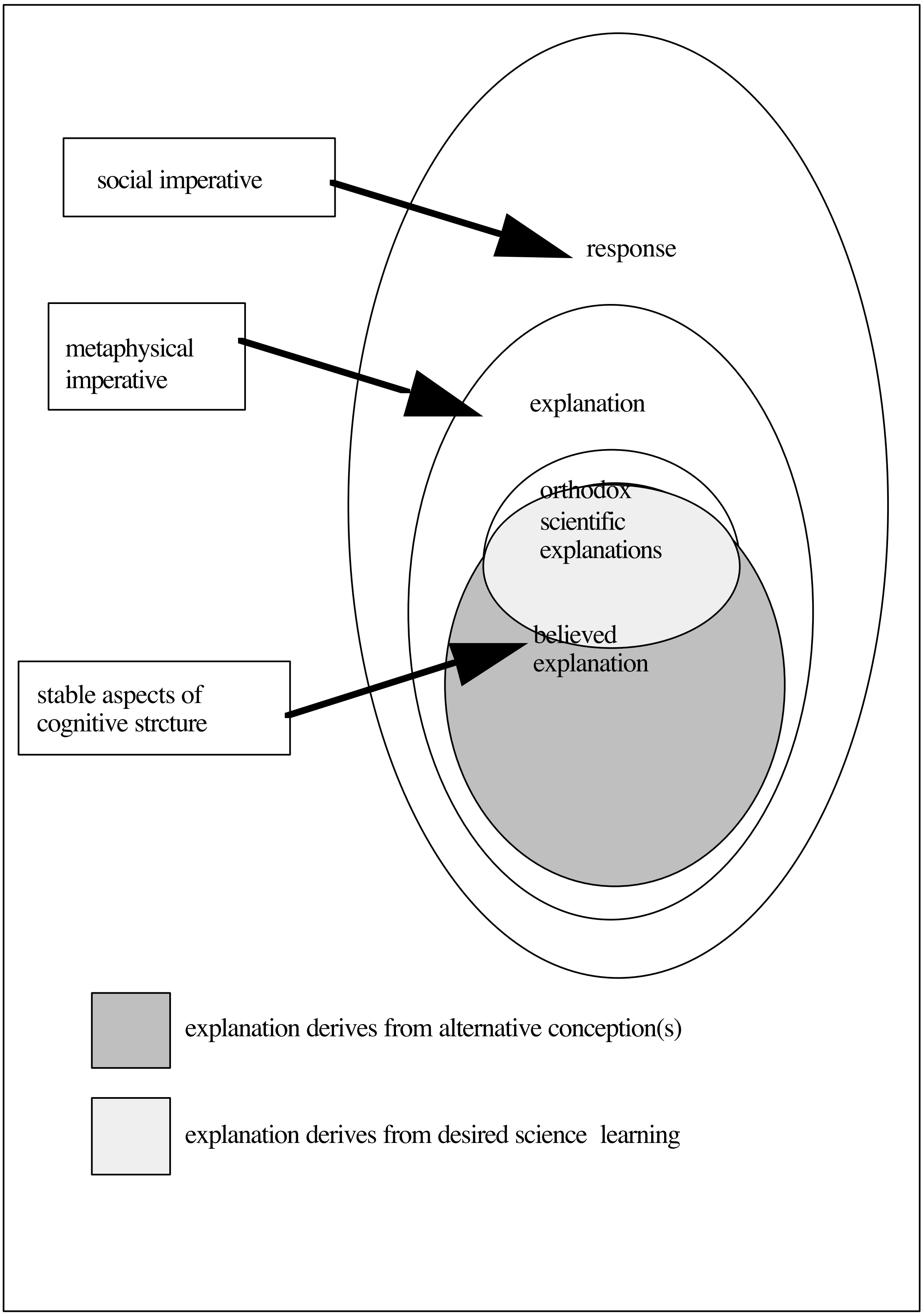

FIGURE 1. *Scientific explanations as a type of response to questioning.*

(iii) resolve inconsistencies. The necessary causality within an explanation allows seeming inconsistencies to be reconciled;
(iv) have a sense of closure across a number of related issues and phenomena;
(v) can generalise over given, or experienced, contexts using related aspects;
(vi) logically possible alternatives are devolved to parallel explanations so as not to introduce inconsistencies within the immediate explanatory system.

TABLE 1. *Characteristics to responses to 'why?'-type questions.*

	Response	*Conception*	*Explanation*
nature	a direct answer to a particular question	composite view which allows limited generalisation to a few associated aspects and data	an extended conceptual device used to resolve inconsistencies within a prescribed system
purpose	fairly isolated reply which serves the immediate purpose of satisfying the questioner	a 'self-sufficient' view which has some durability and appeal over time for the construer	is intended to be 'audience sufficient' and has considerable durability over time
degree of consistency	no felt need for consistency or closure conclusive in intent	a degree of consistency so that inconsistencies can be felt when challenged	has consistency and 'closure' over a certain domain of phenomena; if inconsistencies occur, then other explanatory systems are invoked
plurality	no necessary logical relationship with other utterances	can be qualified to allow logically possible alternatives	logically possible alternatives are accepted as parallel explanations;
degree of integration within cognitive structure	may or may not imply a deeper level of connectedness with knowledge structures	some interaction with other relevant phenomena, but no felt need to be consistent between conceptions.	some need to be consistent between explanations.

Explanations in chemistry

Chemistry uses a wide range of models and theories to explain empirical data (e.g. Carr, 1984; Taber, 1995a). We expect chemistry learners to acquire familiarity with the theoretical frameworks of our science, and to develop some level of proficiency at applying their knowledge to produce explanations. There is a good deal of work looking at various aspects of students' understandings of the subject. Misconceptions in a number of topics have been explored (Schmidt, 1991, 1992, 1997; Garnett et al., 1992.), and common alternative conceptions/frameworks have been uncovered (Briggs & Holding, 1986; Brook et al., 1984; Taber 1998a).

The Understanding Chemical Bonding Project

This paper uses examples of chemistry students' explanations to illustrate our ideas about the nature and quality of students' explanations in chemistry. The primary source of data used in this research derives from interviews with students in the U.K. (in a College of Further Education in England) studying chemistry at University entrance level (the Advanced Level Chemistry examination of the General Certificate in Education). These interviews were undertaken as part of a longitudinal study of the development of students' understanding of the chemical bond concept (Taber, 1997a). In the Understanding Chemical Bonding project sequences of in-depth interviews - over periods of many months - allowed case studies of the progression in individual learners' thinking to be investigated (Taber, 1995b, Taber and Watts, 1997). The research uncovered common patterns in the thinking of chemistry students (Taber, & Watts, 1996, Taber, 1998a, 1998b). The data collected has provided us with a large bank of student explanations, which has been interrogated to develop our analytical model of learners' explanations in chemistry.

METHODOLOGY

The Understanding Chemical Bonding project followed a grounded theory approach (Charmaz, 1995; Glaser & Strauss, 1967; Glaser, 1978), using a variety of data collection techniques, and an inductive analytical approach. The details of this methodology have been discussed elsewhere (Taber, 1994a, 1997a, 1997b). The main data source used in this paper is the transcripts from interviews carried out for this research.

The interviews were all carried out by the same interviewer (KST) who also taught the subjects. The students were considered as co-learners in the research: that is both researcher and co-learner entered the interview context hoping to benefit from the exploration of the students' ideas (Taber 1994d). The interviews were semi-structured in that prepared diagrams were used as interview foci, and some prepared questions were used (including some specifically addressing points from earlier interviews with the same student). All students were interviewed in familiar surroundings and all were recorded on cassette tape with the students' knowledge and consent.

ANALYSIS

Identifying explanations

The first problem is to identify a learner's explanation, or *potential* explanation. Perhaps a simplistic approach is to consider an explanation to be *a response to a 'why' question*. Consider this extract from an interview with Annie, an A level chemistry student:

1 I: We're looking at [Figure 2]. And I wonder if you can tell me what you think it's meant to be?
2 A: It's sodium.
3 I: Why do you think it's sodium?
4 A: Because its got two full shells and then its got one in the outer shell.

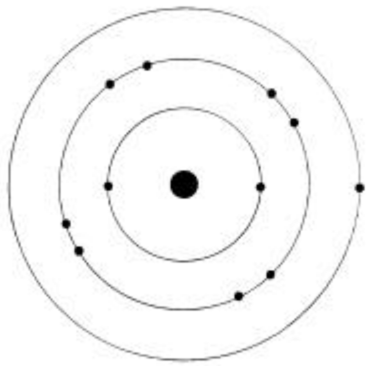

FIGURE 2. *Focal figure presented to chemistry student Annie.*

In this brief extract information is elicited from Annie to investigate her understanding of aspects of her chemistry course. There are two questions, and two responses. The first question (1) elicits a simple a simple ‘factual’ or ‘conviction’ response:

- Figure 2 represents sodium

or

- I believe Figure 2 represents sodium

For the moment it does not matter whether Annie was correct (she was), or precise (perhaps she should have specified an atom, so as not to confuse the sodium atom with the material sodium).

The second question is different in nature, and elicits a more complex type of response. The question is a ‘why’ question, which asks the learner to *justify* their belief. The answer has the form of an explanation, in that it includes ‘because’. The form of the explanation is:

- (I believe Figure 2 represents sodium) *because* its got two full shells [of electrons] and then its got one [electron] in the outer shell, (and an atom of sodium has got two full shells [of electrons] and one [electron] in the outer shell).

As is often the way with dialogue, what is actually said often conveys - through the conventions of oral language - much that is unsaid (Kvale, 1996; Stubbs, 1983). This creates difficulties for analysis: maybe Annie was referring to something other than electrons? (It is not unknown for learners to mis-identify parts of diagrams showing atomic and molecular structures). It is harder to believe that Annie did not imply in her answer that it was ***sodium that*** *has got two full shells and one in the outer shell*, because without this assumption her response ceases to be an explanation! Of course Annie’s explanation could be inferred to mean something ‘stronger’: i.e. that

- (I believe Figure 2 represents sodium) *because* its got two full shells [of electrons] and then its got one [electron] in the outer shell, (and ***only*** an atom of sodium has got two full shells [of electrons] and one [electron] in the outer shell).

This would be chemically incorrect as the diagram could represent Mg^{+} or some other ion.

The main point we are making here is simply that we believe that utterance 4 is an explanation, whereas utterance 2 is not. If we can *identify* explanations, such as Annie's, we can start to consider features of such explanations which may be of significance. So in the example above we might judge that Annie's belief (that the diagram showed sodium) was soundly based (as a sodium atom does have the electronic configuration shown), although she could have been more explicit in explaining that she was referring to an atom, and the arrangement she mentioned was of electrons.

This simple example gives us two clues to identifying explanations: they are often responses to 'why' type questions, and they often include conjunctions such as 'because' (other possible markers might be 'so', 'therefore', 'as', 'consequently' and so forth.) We will refer to exchanges where the learner's utterance includes such words as having the surface structure - or features- of explanations.

The quality of learners' explanations

Given that we can now recognise what is *potentially* an explanation, we are in a position to begin to ask '*what makes a good explanation?*'. Here IT WILL BE suggested THAT much that is presented as explanation does not meet the criteria discussed above, and is better considered as pseudo-explanation.

Pseudoexplanations - 1. confusing 'why it is', and 'why I think it is'!

Firstly, it should be stated that just because a learner responds to a why-type-question, with a *because-type-response*, this does not necessarily provide a *genuine* explanation. One may think of computer programmes that are able to respond to input with grammatically correct responses. (Consider, for example, arguments about the Turing test, and the Chinese room problem, Gardner, 1977, pp.171-177; Penrose, 1989, pp.6-13.)

A learner's *because-type-response* may or may not relate to true belief. As discussed above, Piaget classified children's answer to questions into categories (1929, p.21-28): 'spontaneous conviction', 'liberated conviction', 'suggested conviction', 'romancing' and 'answer at random'. The problem of leading questions (Powney & Watts, 1987, pp.136-137) is clearly particularly significant for those interested in learners' explanations. The importance of asking questions and interpreting responses from within 'neutral ground' has been highlighted by Johnson & Gott (1996), and Kvale emphasises how it is important in interviews to ask a sufficient variety of questions to ensure the interview is self-interpreted (1996). However, even a non-leading question, asked from within neutral ground, does not solve the problem of learners who given random answers, or 'romance'.

Piaget was mostly working with young children, and we may not expect this type of response to be as common with adolescents and young adults. The case of Carol suggests we still need to be on our guard though. Carol was an A level chemistry student who "would rapidly suggest ideas, agree with herself, contradict herself, disagree with herself, decide she was talking nonsense, and suggest something else" (Taber, 1992). Consider Carol, being asked about the diagram shown in Figure 3:

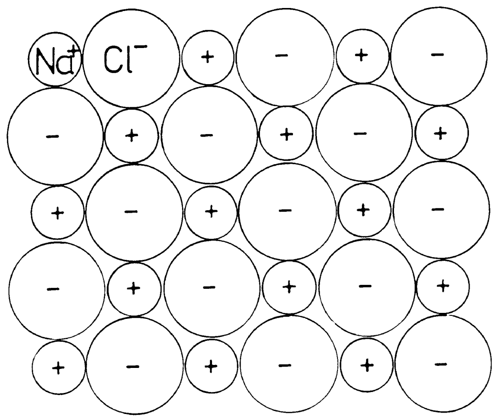

FIGURE 3. *Focal figure presented to chemistry student Carol.*

Carol had suggested there was ionic bonding represented in the diagram. She was asked how many ionic bonds each ion formed.

1 I: How many ionic bonds has each ion got?
2 C: I'd say each bond has got one.
3 I: Right, so this [chloride] ion here, can you show me where its ionic bond is?
4 C: Erm, oh no! Hang on. I think it could have seven.
5 I: Right, well this one here - where's its seven? Can you show me its seven?
6 C: I don't know why I said seven, but, erm, [pause] no, I reckon, it can have as many as it wants, as long as it's got electrons to cover how many it does want. Because all the rest just carry on orbiting, I reckon.
7 I: Right, so how many, how many bonds has this one here got?
8 C: Four.
9 I: Four?
10 C: 'Cause it's in contact with four little circles sodium.

In this short extract Carol claims that each chloride ion forms “one”, ”sev
and “four” bonds! It is possible to *rationalise* each of Carol's suggestions - but *she* only offers a rationale for the last suggestion.

Later Carol is asked about the shape of the benzene molecule represented in Figure 4. At first Carol does not offer an opinion on the shape, beyond not thinking the molecule (or anything else!) is really flat. Then, without any further prompting, Carol produces a suggestion for the bond angle: 102°. She then offers two other suggestions: 107° and 117°. Her rationale is also revealed:

1. I: Right. What shape do you think that molecule is? I mean it's drawn there as being a flat shape, do you think that it will be a flat shape?

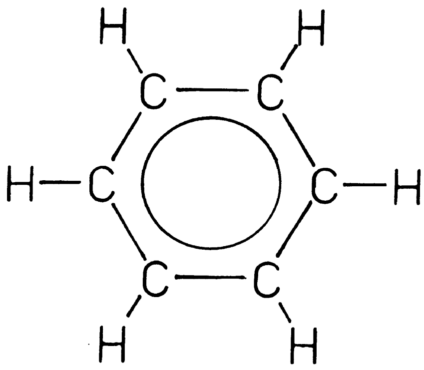

FIGURE 4. *Focal figure presented to chemistry student Carol.*

2. C: No, I don't think so, because I don't think anything's really flat. But, I don't really know what shape it would be.
3. I: Okay.
4. C: Oh! Hundred and, is it a, sorry. Is it a hundred and two degrees, is it, or something, between two carbon bonds?
5 I: Is it?
6 C: Well, I remember a hundred and two somewhere, or a hundred and seven, or it could be a hundred and seventeen, but I think it's a hundred and two, but it's a hundred and, I just remember reading it somewhere.
7 I: Definitely a hundred and something?
8. C: Yeah. But I think it's a hundred and two, dunno why. But, in this bit here.
9. I: The internal angle between two carbon-carbon bonds, that carbon-carbon-carbon angle in there?
10. C: Yeah, I reckon it's a hundred and two. I don't know why, but I just remember reading it, somewhere.

So although Carol offers three possible bond angles, she does not offer any rationale for her answers *in terms of the concepts and models of chemistry* (such as valence shell electron pair repulsion theory for example). Does Carol's response count as an explanation? Certainly her first utterance (2) in this extract takes the form of an explanation:

• I don't think [the molecule is really flat], because I don't think anything's really flat.

Carol justifies her belief about this molecule in terms of a general principle - perhaps an ontological commitment - that nothing is really flat. Her explanation for the bond angle being 102^o (or $107\ ^o$ or $117\ ^o$) however has a different nature - an appeal to authority. This has the *surface feature* of an explanation,

• I believe the bond angle is $102\ ^o$ because I remember reading it somewhere.

Whilst not wishing to deny the importance either of authorities (such as teachers and texts) nor of recall of information, this example demonstrates an important distinction we would wish to draw about learners' explanations. This is the distinction between explaining *why* something is so and explaining how one knows it is so

In this case Carol explains *why she thinks* the bond angle might be 102°, but she does not offer an explanation of why the bonds angle *would be* 102 °. There is an important literature into learners metacognition (e.g. Gunstone, 1994, pp.131-146) and we would consider learners' knowledge about their own knowledge (its sources, its limitations, its changeable nature etc.) as of great importance. On other occasions during the same interview session reported above Carol evaluated her own answers, giving the impression that she was somewhat surprised by what she had said,

> "I don't know what that's got to do with it though"
> "what I've just said, I don't agree with"
> "but that don't make sense really"
> "I nearly said the right answer"

Indeed evidence from other chemistry students suggests that learners are not always aware of the distinction drawn between 'why it is' and 'why I think it".

We would suggest that when discussing explanations it is useful to think in terms of *levels of explanation*. In science, our explanations derive from conceptual frameworks that are complex (and often hierarchical), and so that what is an explanation in one situation, is also something to be explained within another aspect of the wider scheme of scientific knowledge. So, taking an example which will be relevant to our next illustration from the database, one might consider a series of nested questions and responses, where each explanation may the source of a further question:

Q: why does water dissolve salts?
R: because it is a polar solvent
Q: why is water polar?
R: because it is a compound of two elements which have different electronegativities?
Q: why is that?
R: oxygen is more electronegative than hydrogen.
Q: why?
R: oxygen has a core charge of +6, whereas hydrogen - although a smaller atom - only has a core charge of +1
Q: why does oxygen have a core charge of six?
R: because it has a nuclear charge of +8, and an electronic configuration of 2.6, and so (at a simplistic level) the electric field experienced by the outermost electron is equivalent to that of a +6 charge

This story could run and run, with discussion of nuclear structure, the vector nature of field quantities, discussions of the degree to which orbitals in different shells overlap, etc. The point is that such a sequence does not only *broaden* the explanation being given, but also *deepens* it to other levels of explanation. The first response, by itself, only explains by providing a label ('polar'). This would only be a valuable explanation if the person receiving it was able to provide the background knowledge of what 'polar' is, and its significance. Subsequent responses place the label within an increasingly extensive conceptual framework. Space does not allow a thorough discussion here, but we might suggest that discussion of charges is at a deeper level of explanation than the use of the concept electronegativity - it is at a 'higher' [sic] level in the hierarchy of scientific concepts - i.e. the concept electronegativity may be somewhat subsumed under the area of electrostatic phenomena, where charge is a fundamental concept.

Pseudoexplanations - 2. circularity in students' arguments

This brings us to another example of a pseudo-explanation: Umar's tautological explanation of polar bonding. Umar, an A level chemistry student (i.e. c.17 years old), was asked about the type of bonding in tetrachloromethane.

> "It's like polar, 'cause it's between ionic and covalent, 'cause it's somewhere in between, like the electrons might be pulled more strongly towards the chlorine than the carbon, 'cause the chlorine's more electronegative."

Umar gave an answer, the bond was "like polar" which he justified with a reason "it's between ionic and covalent, 'cause it's somewhere in between". He then described an important aspect of such a bond, that "the electrons might be pulled more strongly towards the chlorine than the carbon" and gave a reason for this - because "the chlorine's more electronegative."

Umar's answer certainly counts as an explanation: his answer is justified in relation to other possible responses (ionic and covalent), the idea of the bond being between these two is explained in terms of where the electrons would be pulled, which is itself justified in terms of a theoretical construct: electronegativity.

In the interview Umar was probed to see how much further his understanding might stretch, and in particular what he understood by 'electronegativity'. Umar reinterpreted his description of the polar bonds in terms that the electrons would "spend more time at the chlorine than the carbon", and so this was followed up:

1 I: So why do they spend more time at the chlorine than the carbon?
2 U: 'Cause chlorine's more electronegative.
3 I: What does that mean?
4 U: It's got more tendency to attract an electron from another atom.
5 I: What more, more than carbon?
6 U: Yeah.

To the interviewer, Umar's explanation was becoming circular: the electrons were pulled more to the chlorine because it was more electronegative, and that meant that it would pull the electrons more! What was of interest here was whether Umar saw this logic as circular:

1 I: So we're saying that the electrons are going to be nearer chlorine, rather than carbon, and the reason for that is because chlorine's more electronegative,
2 U: Mm.

3 I: And the reason for that is because chlorine attracts the electrons more than the carbon. So what's the reason the chlorine attracts the electrons more than the carbon?
4 U: It's got the greater tendency to like attract an electron from another atom.
5 I: Mm. But does that explain it?
6 U: I think so.
7 I: You think so. So if we looked at the bond, if we could see the bond, you know, we'd see the electrons aren't actually in the middle, they're nearer which end?
8 U: These spend more time towards the chlorine.
9 I: And so because of that, we have a name for that, and we say that chlorine is more,
10 U: Electronegative.
11 I: And electronegative simply means it's got a greater tendency to pull the electrons towards itself.
12 U: Yeah.

So Umar seemed to accept his tautological answer as having explanatory power.

It would be possible to leave this example at this point, but interestingly when Umar was asked again whether this was an explanation, he moved into a new area:

1 I: Have we actually explained why that happens?
2 U: Yeah, 'cause like it's it it's got, it's got a, it *wants to* fill up its last shell, its outershell.
3 I: Doesn't the carbon though?
4 U: Yeah but that's got, that *needs* more electrons to fill it up. So, the chlorine's got more, as it's got core charge, maybe, more core charge on the outer electrons than the carbon's got, more core charge on its outer electrons, so it might pull it towards it more.

The new area reflects a range of interesting points. Umar uses anthropomorphic language, brings in a common (for students) explanatory device of full shells, and the notion of core charge. This latter idea is relevant to explaining differences in electronegativity, and therefore taking the explanation of the polar bond to another level,

1 I: So you've introduced a new idea now, of core charge,
2 U: Yeah.
3 I: you hadn't mentioned that before.
4 U: No.
5 I: So what's the core charge?
6 U: The charge the nucleus has on the outer electrons.
7 I: So which would be more, chlorine or carbon?
8 U: Chlorine.
9 I: Right, and why would it be a larger core charge? Can you explain that?
10 U: 'Cause it's like, it's got seven electrons in it's outer shell, so the core charge will be plus seven. Whereas on the carbon it's got four electrons so the core charge will be plus four, so it will attract the electron from the other carbon atom 'cause it ain't got as strong as core charge as the chlorine.

There are a number of features of Umar's explanations which are of interest, but the two which we would like to highlight here are:

(a) Umar's apparent acceptance of a circular argument, without any apparent awareness of the impotence of such tautology;
(b) the presence in cognitive structure of further relevant material which could be accessed when Umar was given more time, and probed to look beyond the tautology.

Pseudoexplanations - 3. vagueness limits predictive power

The term pseudoexplanation is used here for something that has the superficial (surface) features of an explanation, but which lacks any explanatory content. The criterion here should be *does the 'explanation' have any useful predictive power*?

Consider Tajinder, a second year A level chemistry student when he was asked about his understanding of multiple bonding. He began by providing a definition of what this means:

> "Multiple bonding takes place between two atoms when there's more than

As this is an abstract explanation (at the unobservable molecular level) he was asked how he could tell if a hydrocarbon compound had multiple bonding. Tajinder suggested that he could use the "physical properties" and explained that in the example of ethane and ethene, one could consider 'breaking up' the molecules "into carbon and hydrogen atoms". In his view "it would take a lot more energy to break the ethene molecule up than the ethane", and this was "to do with the

Tajinder's explanation so far may be judged to be promising: he has related a theoretical concept (the multiple bond) to a property of molecules that could in principle be measured - at least on a molar scale. What his explanation so far lacks is the theoretical, logical, link between the notion of "more than one bond" and the need for "a lot more energy" to break up the molecule. This is particularly important in exploring the nature of Tajinder's explanatory scheme, as canonical chemistry would suggest the opposite result to that Tajinder predicted.

Perhaps Tajinder could suggest a logical chain from his understanding of the distinction between multiple and single bonds, and his expectation that the alkene would have greater atomisation energy? In fact when Tajinder was asked 'why', no such chain was forthcoming. Rather he explained his prediction, thus:

> "because of the structure of the molecules, and the way they're arranged and the bonding, 'cause it's multiple bonding, more than one bond."

At this point it seems that Tajinder's original answer - that the presence of a multiple bond would effect physical properties - was not part of a logically connected explanatory scheme. Rather, Tajinder had learnt a rote connection. Tajinder's comments can be paraphrased to see their explanatory worth:

> atomisation energy of ethene is greater than ethane (incorrect) *because* ethene has a double bond (true).

This has explanatory form - or surface structure - as one 'fact' is explained by another (as denoted by the use of 'because'). That the explicandum is incorrect, does not in itself negate

Tajinder's explanation. One might assume that - almost by implication - Tajinder's explanatory scheme includes a step that 'breaking bonds requires energy'. It is also possible to postulate (although there is no evidence in what he has said so far) that he is using the principle that *a double bond requires more energy to break than a single bond*. We could reconstruct this scheme:

> atomisation energy of ethene is greater than ethane (incorrect) *because energy is required to break bonds, and* ethene has a double bond*, which require more energy to break than a single bond.*

(Of course such an explanation breaks down because - compared to ethane - ethene has a double bond *rather than three single bonds*!)

However, Tajinder's actually presented explanation was

> "to break up [a] molecule into carbon and hydrogen atoms, it would take a lot more energy to break the ethene molecule up than the ethane"

and this was "to do with the bonding",

> "because of the structure of the molecules and the way they're arranged and the bonding, 'cause it's multiple bonding, more than one bond."

At one level Tajinder has provided a response that (leaving aside its validity) has explanatory power: the presence of multiple bonding will increase atomisation energy. However, when pressed to develop his explanation to the next level, all he can offer is vague references lacking any predictive use ("the structure of the molecules, and the way they're arranged"), and a circular reference back to his definition ("the bonding, 'cause it's multiple bonding, more than one bond"). Tajinder's explanation here is represented in Figure 5.

Sometime later in the interview Tajinder listed some of the differences between ethane and ethene, and again suggested "their physical properties". Tajinder now gave the examples of "maybe boiling temperatures and melting temperatures". His reasons for these being different for the two compounds were "because of the structure of the molecule, the shape of the molecule". Again no detail was given to provide any predictive power. Figure 6 adds this additional feature. The explanatory scheme, as shown in Figure 6 represents the three parts of Tajinder's explanation. Two aspects were too vague to be of predictive use (structure, shape) and the third, bonding, was circular and led back to his initial definition without providing any deeper level explanation.

Complexity of explanations

Consider the following extract from a research interview where chemistry student Tajinder attempts to explain why salt dissolves in water, despite there being bonds holding the sodium chloride crystal together:

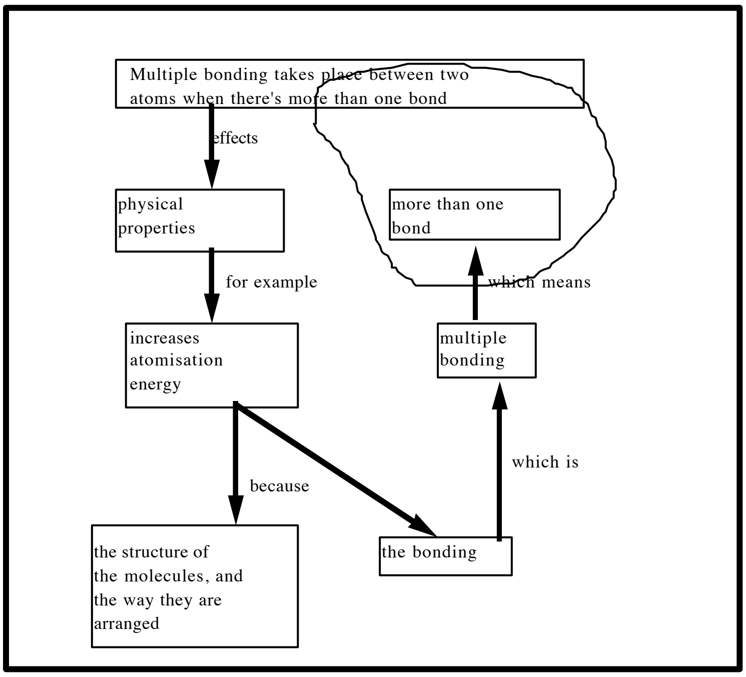

FIGURE 5. *Tajinder's initial explanation of the effect of multiple bonds.*

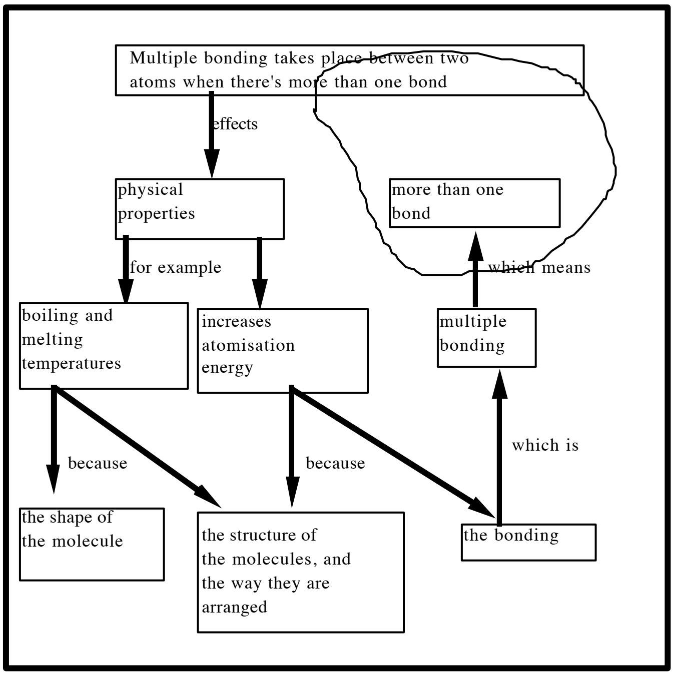

FIGURE 6: *Tajinder's fuller explanation of the effect of multiple bonds.*

1 I: How does the water break the bonds?
2 T: It's to do with hydration energies.
3 I: Oh yeah, what's that?
4 T: I think, when you have Na^+, as a centre ion, the water molecules surround it, with the O which is the minus part facing it, so they all come around, they all just attack it, not really attack, but they're just attracted to it. And this formation, sort of helps break the bond of the Na and the Cl.
5 I: But don't you need energy to break bonds?
6 T: Yes.
7 I: So where does the energy come from?
8 T: The water itself.
9 I: So does it get really cold when you do this? When you dissolve salt in water does it get really cold?
10 T: No.
11 I: So where does the energy come from then?
12 T: I think what it is, when we have the water molecule, it's sort of a two way process, the water molecules have hydrogen bonds between them, and these need to be broken, and the NaCl have bonds which need to be broken as well, and as these break, they give off heat, don't they? No, as when bonds are broken, they need heat, don't they, to be broken, and when they form they give off heat.

Tajinder was unable to produce an explanation which he was satisfied with. His problem was that he knew energy was required to break bonds, and he could only suggest this came from the water. Yet, this would lead to the water getting colder as salt dissolved - something that he did not believe happened.

And yet Tajinder had already provided the missing pieces of this particular logical puzzle. He had started his explanation by suggesting that "the water molecules surround [the ion] "they're just attracted to it. And this formation, sort of helps break the bond of the Na and the Cl", and had later reported that "when [bonds] form they give off heat".

It is interesting to consider how Tajinder's utterances could be rearranged:

I: How does the water break the bonds?
T: "it's sort of a two way process" "the water molecules have hydrogen bonds between them, and these need to be broken, and the NaCl have bonds which need to be broken as well" "when bonds are broken, they need heat, and when they form they give off heat." "It's to do with hydration energies." "when you have Na^+, as a centre ion, the water molecules surround it, with the O which is the minus part facing it, so they all come around, "they're just attracted to it." "And this formation, sort of helps break the bond of the Na and the Cl."

This composite puts together Tajinder's ideas in a way which seems to provide a satisfactory answer, and so we are left with the question, *why couldn't Tajinder do this?*

Our suggestion here is that the tasks of verbally composing the explanation was too complex. Although Tajinder was able to retrieve sufficient information from cognitive structure to provide a satisfactory explanation, he could not keep all the relevant factors 'in mind' at once. By the time he has explained about the bond breaking and how this related to energy changes, he had 'forgotten' that he had already proposed an exothermic step in the overall process.

Scientific and alternative explanations

Where a learner produces a response to a 'why'-type question, which has the surface structure of an explanation, and which addresses the initial question in a way which is logical and coherent, we may consider this to be a true explanation. This does not mean it is a correct explanation, from the orthodox consenual scientific perspective. Tajinder's attempt at explaining solubility, above, is couched in terms that are appropriate to a pre-University chemistry student. His explanation is scientific, if not in this case complete. It would be possible to produce many other examples from the database which show students constructing scientific explanations for chemical phenomena: explanations that vary on such dimensions as coherence, completeness and complexity.

However, the database also contains many other explanations which although they may be presented logically, and address the questions asked, draw on alternative conceptions. Consider Noor's explanation for why atoms of different elements have varying electronegativity:

I: Could you explain why some atoms should be more electronegative than others?

N: In all cases what an atom is trying to do is to become stable, and so obtain a full outer shell. In the case of metals it's easier for them to become stable by losing electrons, and by doing this they become positive, so they're going to be more electropositive, whereas non-metals, to become stable, would acquire those electrons, and hence become more electronegative, because they've gained electrons.

There are several points of interest here. For one thing there is a *suggestion* that Noor has confused cause and effect. Are metals electropositive because they form positive ions, or do metals form positive ions because they are electropositive? (This is *only* a suggestion, as this short extract alone is not sufficient evidence: perhaps Noor is just imprecise in the wording of her explanation.) Less ambiguous is Noor's statement of her belief that the behaviour she has been asked about can be explained by a basic principle of chemistry: the full shells explanatory principle. This is the central principle of the octet framework, a common explanatory framework used by chemistry students (Taber, 1997a, 1998a). Noor starts her response by stating the central principle upon which her explanation will be based: "*In all cases* what an atom is trying to do is to become stable, and so obtain a full outer shell." She then built upon this principle by distinguishing between metals and non-metals, and relating the electronegativity of these two groups to how they went about achieving full shells.

It is possible to analyse the structure of Noor's explanation. It reads like an explanation: with clauses connected by "so', "whereas" and "hence". She states that it is easier for metals to lose electrons than gain electrons, and that this causes them to be positive. 'Easier' here *could* be an informal notion of the enthalpy change involved (which would be scientifically correct), although it may mean something less specific. The consequence - that the metal becomes positively charged - is logically correct.

Of course no matter how valid the logic, or how well the explanation is structured, Noor's response is not good science. The octet framework is an *alternative* conceptual framework (Taber, 1998a), and Noor's response - based on it - is an alternative explanation, not a scientific explanation.

One aspect of Noor's argument that is of note, because it is a common feature in chemistry students explanations (Taber & Watts, 1996), is its anthropomorphic nature: in all cases what an atom is *trying* to do is to become stable. Such language has explanatory currency only where the implied actor is actually animate and capable of 'trying'. Many other examples of such anthropomorphic uses of language have been found: atoms want, need, require, think, prefer, like, are eager, etc. (Taber, 1997a).

DISCUSSION

One key point arising from our discussion of chemistry students answers to questions is that we can distinguish between responses that are not framed as explanations, and those that are; and we can further distinguish between pseudoexplanations and true explanations. The quality of true explanations can also be judged by various criteria, but a common concern will be its match to accepted science - i.e. we can distinguish between alternative and scientific explanations.
Three key questions to be asked, then, about learners' utterances, to judge their value as explanations are:

(a) does the utterance have the surface features of an explanation ("because", "so", "therefore",

(b) is the utterance logically consistent in its own terms, and does it match the accepted criteria for a good explanation?
(c) does the explanation match the norms of curricular science (is the chemistry 'right'?)

Learners' answers to our questions, and their spontaneous attempts at explanation may be classified in the terms shown in Table 2.

TABLE 2. *A simple classification of explanations.*

(a) surface structure (of an explanation)	*(b) logically coherent /sound*	*(c) scientifically correct*	*status as an explanation*
no	not applicable	not applicable	not an explanation
yes	no	not applicable	pseudoexplanation
yes	yes	no	alternative explanation
yes	yes	yes	scientific explanation

Pseudoexplanations may be characterised as *because-type-responses* to *why-type-questions* which do *not* logically fit the phenomenon to be explained into a wider conceptual scheme. It may be that the attempt at explanation is too vague or the logic itself is faulty, or the 'explanation' could be circular, or simply call on the way things are, or make some appeal to authority. Pseudoexplanations may concern '*I know* that is because', rather than '*that is* because'. Space has not allowed us to illustrate *all* the possible ways that a pseudoexplanation falls sort of the standards of scientific explanation, but some possible features of pseudoexplanations include:

(i) tautology
(ii) teleology
(iii) anthropomorphism
(iv) 'explanation' by labelling
(v) 'explanation' by description

(vi) confusing cause and effect
(vii) confusing correlation and causality
(viii) faulty logic
(ix) confusing the reason *why something is the way it is*, with the reason they have *for believing* it is that way.

Formally correct explanations may often be judged according to whether they match accepted scientific models. This is appropriate in many situations (for example when undertaking research into the nature of students conceptions), but if we are interested in a student's ability to *understand the nature of explanation*, and *to construct explanations*, the distinction between scientific and alternative explanation is less important.

Alternative explanations call upon alternative conceptions, and may relate to common alternative conceptual frameworks. We suggest that the existing canon of work on learners' ideas in science has focused heavily on the distinction between scientific and alternative conceptions - whilst ignoring learners' abilities to structure explanations. It is a moot question whether the student holding a scientific conception in cognitive structure but unable to structure an explanation to apply it, should be considered to have better potential in science than the peer who can eloquently apply an alternative conception. At the very least we would suggest that both present the science teacher with work to do.

As important as the orthodox/alternative status of explanations is the question of the stability of the conceptual schemes that provide the resources for the student's explanation. Some explanations produced by students may be reports of stable aspects of cognitive structure, that are recalled in response to a question. Others may be largely constructed in situ to deal with a novel question, but using stable conceptions from coherent and unambiguous aspects of cognitive structure. Still other explanations may be 'cobbled together' from whatever cognitive resources may come to mind, and may not reflect stable and well integrated aspects of the respondent's cognitive structure.

This brings us to the question of commitment to a response. We have seen that explanations are the product of a social context with imperatives to explain. The explanation generated by a student may be believed or not. Again there is a spectrum of possibilities from the explanation that is based on a deep commitment, through the explanation that the respondent firmly believes *is* the scientific explanation *although the respondent is not actually convinced by the scientific explanation*, to the 'romanced' or random answer that attempts to satisfy the social imperative rather than reflect any beliefs about the actual cause of the phenomenon.

So having distinguished responses which do not meet our criteria for true explanations (various forms of pseudoexplanations) from those that do, we then find that there are at least three further dimensions upon which these formally correct explanations may vary: (a) the match of the science content with orthodox science; (b) the extent to which the explanation derives from stable aspect of cognitive structure; and (c) the extent to which the explanation is believed by the explainer. In principle we may locate student explanations at any point in a three dimensional space as shown in Figure 7.

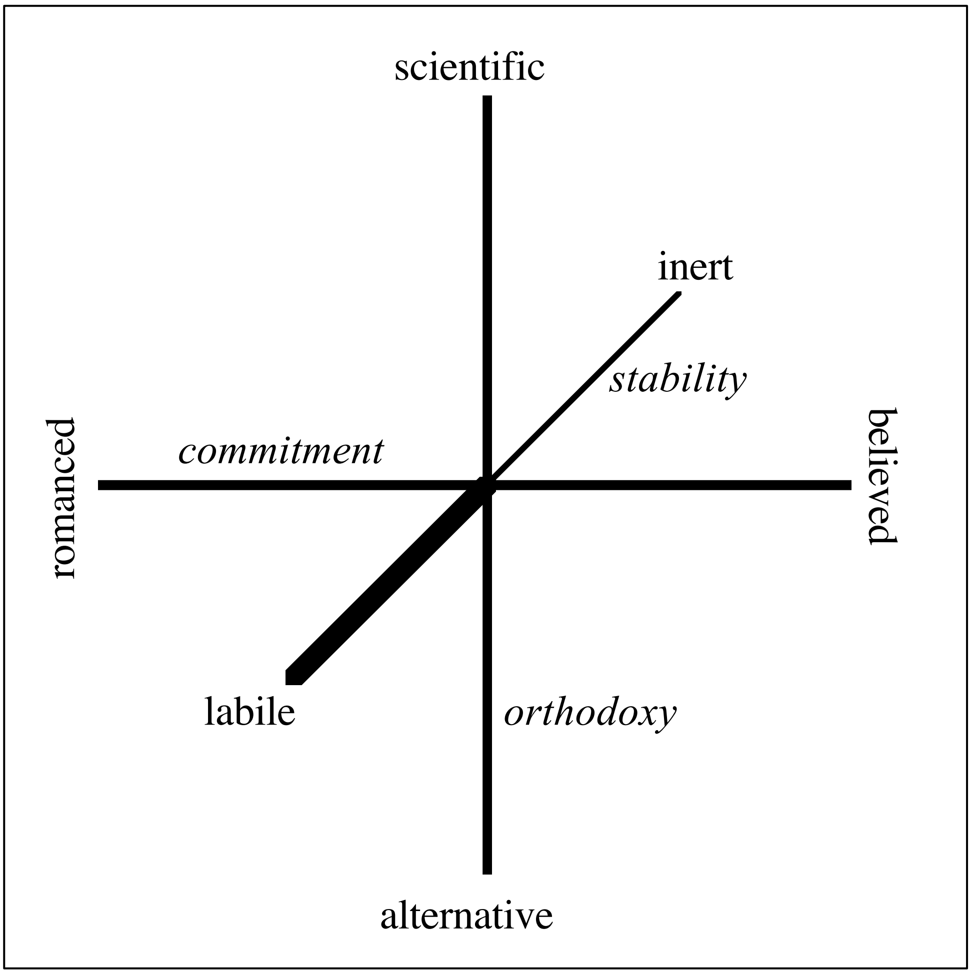

FIGURE 7. *Dimensions of student explanations.*

This paper focuses on how students produce explanations in chemistry. This work is somewhat provisional in nature, and may be seen as suggesting a framework that should be tested in the context of a wider range of data (in terms of different ages ranges, various science topics and so forth.) However, we hope to have both (1) highlighted some of the key aspects that may be significant in exploring students' explanations, and (2) synthesised features from a number of distinct areas of research that may illuminate both the structure and quality of students explanations in chemistry.

In particular our discussion of specific illustrative data have highlighted how further research is needed to find out how well students understand the nature of explanation in chemistry. It has been shown that *deficient explanations may not always be due to lack of appropriate chemical knowledge*. Our exploration of examples of student explanations leads us to ask whether teaching about the role, and structure, of effective explanation should be made an explicit part of the chemistry curriculum. Certainly the work of Driver and coworkers (1996) points in this direction, and such an objective could form part of a wider move to explicitly develop learners' metacognitive abilities (Gunstone, 1994; Taber 1994c).

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